

Habitat Maintenance Flow Requirements for Sand Scour from Cobble Beds

P.M. Hirschowitz, C.S. James

Centre for Water in the Environment, University of the Witwatersrand, Johannesburg, South Africa

Abstract

In terms of the National Water Resources Strategy, objectives are to be set for the management of each river, including “numerical or descriptive statements about ...the character and condition of the instream and riparian habitat.” One particular habitat characteristic (of particular importance to both fish and benthic invertebrates) is the extent to which the spaces between closely packed cobbles and boulders on the river bed are filled with interstitial sand, as this sand is deposited and scoured by the flow. A relatively new approach to this type of problem rests on the assumption that, while particular hydraulic conditions occur, the interstitial sand pattern will tend at a specified rate towards a certain equilibrium state. This state can be defined in terms of spatial dimensions of the sand fill pattern, for example average depth of free space. The results of laboratory experiments aiming to define and predict this equilibrium state, and the rate at which this state is approached, are presented. Finally, the planned incorporation these findings into predictive computational models for prescription of flushing flows is discussed.

Keywords: *flushing flows, interstitial sand, cobble-bed, sand scour, embeddedness.*

1 Introduction

1.1 Importance of Embeddedness

In terms of the National Water Resources Strategy, objectives are to be set for the management of each river, including “numerical or descriptive statements about ...the character and condition of the instream and riparian habitat.” One particular habitat characteristic (of particular importance to both fish and benthic invertebrates) is the extent to which the spaces between closely packed cobbles and boulders on the river bed are filled with interstitial sand, as this sand is deposited and scoured by the flow. The presence of interstitial material is commonly referred to as embeddedness. Scouring of interstitial sand and silt can be achieved by flushing flows.

Reiser et al. (1989) highlight the importance of flushing flows for the river ecosystem: “Flushing flows are needed when sediment concentrations exceed historic levels and begin to affect important aquatic habitat and life history functions.” The majority of studies (for example Kondolf et al., 1987, Nelson et al., 1987 and Wu, 2000) have focused on the importance of this type of flushing in order to provide suitable fish spawning habitat. The importance of embeddedness for benthic invertebrates has also long been recognised. In a community level study of the benthic invertebrate distribution of the Vaal River catchment, “the major factor with which the distribution of fauna was correlated was the amount of silt and sand present in the river beds,” (Chutter, 1970). This presence was attributed to “a lack of scouring,” (Chutter, 1970). In a more detailed specification, O’Keeffe and Dickens (2000) focussed on the requirements of several individual South African invertebrate species. Embeddedness is therefore important at species, community and ecosystem levels.

1.2 Surface and Depth Flushing

Flushing of interstitial sand can be divided into surface flushing (within the surface layer of cobbles) and depth flushing (from subsurface layers). “Sand can be scoured from cobble substrate to a depth of one average cobble diameter without cobble mobilisation,” (O’Brien, 1984). However, “to flush fine sediment from deeper than one coarse grain diameter requires at least some motion of the gravels themselves,” (Kondolf and Wilcock, 1996 quoting findings of Beschta and Jackson and Diplas and Parker). Surface and depth flushing must therefore be analysed in different ways. Depth flushing is predicted by flows required to mobilise the cobbles. Surface flushing can be predicted based on sand properties and hydraulic characteristics. This study focuses on surface flushing only.

1.3 Quantifying the filling of interstitial spaces within the surface layer

In order to investigate or model changes in the sand content of cobble beds, it is necessary to define embeddedness in a quantitative way.

Osmundson et al. (2002) measured the following quantities in the Colorado River:

- “Depth of free space [which is the] absolute distance from the top of surficial rocks to the point where rocks are embedded in fine sediment”
- “Proportion of ... surface area consisting of fines”
- “Interstitial Void Volume” percentage
- “Percentage of surface layer consisting of fines”

All of these quantities were correlated (although with considerable scatter) both with each other and with various biological measures. This relation should be expected, since these measures are directly related through geometry and will differ relative to each other only through the effect of particle shape, size distribution and deposition patterns on these geometric relations. However, the scatter in these relations shown by the data of Osmundson et al. (2002) means that conversion between different measures would be highly approximate.

Since all of these physical measures were shown to be biologically significant, the choice between measures is primarily a practical question of measurement technique. Mass or volume percentages are commonly used in sediment transport analyses, but this is in any case not the approach adopted. In cases where the water is clear, the proportion of surface area consisting of fines is probably the easiest to both estimate (visually) and measure (off photographs), and has the advantage that it can be measured without disturbing the bed surface. This will therefore be used for some of the results presented here. However, it cannot be easily measured in very turbid water, and cannot be used within subsurface layers. Depth of free space has been used in some previous experiments, and will also be used here to allow direct comparison with these experiments.

1.4 Flow and Embeddedness Characteristics and the Equilibrium State Approach

While the objective of a flushing flow is a defined removal of sand, this must be stated in terms of controllable flow characteristics, which are primarily flow “magnitude, duration and timing,” (Wilcock et al., 1996). “Important considerations [for the timing of flushing flows] include ... the historical run-off period, and ... flow availability. Assuming that our primary concern is for the maintenance of aquatic biota, flow timing should be based upon the life history requirements,” (Reiser et al., 1989). Flow magnitude is related to the local hydraulic conditions producing scour through appropriate hydraulic analyses. This analysis will use two hydraulic parameters commonly applied to predict scour: shear velocity and Shields Parameter for the sand fraction. The three primary factors which must therefore be related by the model of flushing flows are a measure of embeddedness, flow duration and one of the two hydraulic parameters mentioned above.

This study attempts to apply a relatively new prediction approach which I will term the equilibrium state method. This rests on the assumption that, while particular hydraulic characteristics occur, the sediment quantity and / or composition will tend at a specified rate towards a certain equilibrium state. This equilibrium state may be defined in terms of any desired variables. For example, Odiyo (in prep.) defines the equilibrium sediment storage associated with morphological features in terms of total sediment depth or height. Grobler (pers. comm.), defines morphological states in terms of bed slope. Jonker (2002) and Jonker et al. (2002), addressing the particular concern of scour of sand between cobbles, defined the equilibrium state in terms of the depth of free space, which was defined in section 1.3.

The equilibrium state approach allows prediction of flow magnitude and duration. It also contributes a fundamental insight into sediment processes. The principal advantage of the equilibrium state approach is that the state towards which the system is moving can be easily identified. Indeed, for the prediction of the effect of approximately constant sand and water flows over a sustained period, a reasonable assumption may be that this state will be reached. Because this approach considers the effect of each change in hydraulic conditions, full equilibrium state methods are most suitable for modelling shorter durations, and are particularly recommended for the analysis of the effects of single flood events.

1.5 Data Requirements

Application of an equilibrium state approach requires prediction of the equilibrium state (depending on local hydraulic variables and incoming sediment supply) and a prediction of the rate at which a defined sediment property approaches this equilibrium state. This rate will be divided into two components, both of which are important to specify flow duration: the rate at which scour progresses in the downstream direction, and the rate at which scour occurs at a particular position.

1.6 Previous Experiments

O’Brien (1984) measured changes in depth of free space in a model of the Yampa River, using natural cobbles in a recirculating flume. His technique of measuring embeddedness at frequent intervals at several sections along the length of the flume has been adopted for this study. In this way, both the rate of scour at a particular position, as well as the rate of downstream progression can be observed. However, the results of O’Brien (1984) will not be used for direct comparison, as they are reported in insufficient detail.

The most relevant previous data is that of Jonker (2002) (also published in Jonker et al., 2002), who also measured the effect of hydraulic parameters on the depth of free space. Jonker (2002) used clear water i.e. no sediment feed and natural cobbles. The trends which emerge from this analysis are:

- For any particular sediment size, the maximum scour depth increases almost linearly with shear velocity.
- “The effect of cobble size is small, and cobble diameter as such does not seem to play a significant role in the size of the boundary eddies,” (Jonker et al., 2002)

However, neither of these previous experiments provided all of the data specified in section 1.5. Further experiments were needed to determine the relationship between hydraulic parameters and both the equilibrium state and the rate of progression towards this state.

2 Experiments to Determine the Equilibrium State

2.1 Aims

- To relate the equilibrium depth of free space to which sand is scoured between closely spaced objects under clear water conditions to flow condition.
- To quantify the effect of sediment supply on the depth of free space.

2.2 Setup and Procedure

Sand scour tests were carried out in an experimental flume which had a width of 0.38 m, a height of 0.66 m and a length of 15.0 m. Water was supplied to the flume through a closed circulation system via a constant head tank. A valve situated in the supply pipe to the experimental flume was used to control the discharge. The flume test section is rigid, and was set at a various slopes by means of two linked electrically operated jacks. Water surface elevations were measured by means of a pointer gauge with a resolution of 0.5mm. A V-notch weir at the outlet of a stilling basin at the downstream end of the flume was used to determine the discharge using a pre-existing calibration curve. As an independent check on the discharge, a flowmeter is installed in supply pipe from the constant head tank to the flume. Chainage along the flume was measured by means of a tape measure permanently fastened to the wall of the flume.

For series C tests, in which sediment feed was used, a belt feeder was used to supply sediment to the flume. Sediment discharge rates were controlled by adjusting the plough opening at the base of the supply hopper, and were measured by collecting sediment over a fixed period of time observed with a stopwatch, and then weighing. In order to ensure thorough wetting of the sediment, a rectangular overflow weir was constructed inside the flume under the discharge point of the sediment feeder. The turbulence created by the weir ensured wetting. Sediment was conveyed from the feeder to the start of the hemispheres (see below) by means of a raised platform constructed inside the flume.

Sand used for the testing was graded silica sand with a median diameter of 0.47mm, and a measured density of 2440kg/m^3 . A particle size distribution analysis was performed by sieve techniques.

To eliminate inconsistencies due to the variability of natural cobbles, and the consequent difficulty of defining a surface level, 57mm diameter concrete hemispheres were selected to represent cobbles in these experiments. These hemispheres were placed on the flume bed in a staggered, close-packed pattern, as indicated in Figure 1. Approximately 4.5m length along the flume was covered with hemispheres.

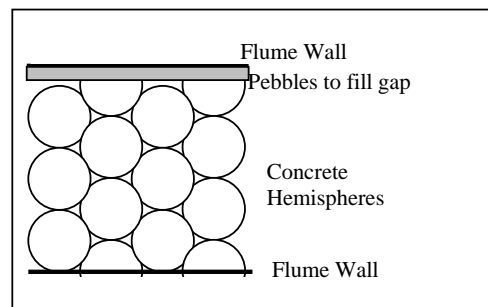


Figure 1: Layout of hemispheres

A test section approximately 0.5m long was selected within the region covered by hemispheres for measurement of sand levels. In the test section, the nine whole hemispheres were marked with rings indicating the height below the top. These rings were used to estimate the depth of free space to the nearest 1mm.

At the start of each test series (A, B etc.) gaps between hemispheres were filled with sand to approximately the level of the top of the hemispheres. For successive tests within the same series, after readings had been taken, the discharge was increased, and a subsequent run was started using the sand pattern from the previous run as a starting point. Photographs of the test area were taken periodically as scour proceeded, and scour was allowed to proceed until no noticeable change could be observed between the current sand pattern and that photographed an hour or more previously. The time required for the sand patterns to stabilise varied from approximately 7 hours to approximately 35 hours for the clear water experiments, and approximately 1 hour for the sediment feed experiments.

Tests were performed as listed in Table 1. Here, the effective flow depth was calculated as the distance from the water surface to 0.3 times the average depth of free space below the average elevation of the top of the hemispheres. (This is in accordance with the effective depth measured by Sumer et al., 2001.) In all hydraulic calculations, side-wall effects were neglected.

Table 1: End of test conditions and Results for Equilibrium State Experiments

Test	Bed Slope	Dis-charge	Effective Flow Depth	Sand Feed Rate	Water Surface Slope	Energy Slope	Shear Velocity	Shields Parameter for sand	Final Depth of Free Space (mm)		
		(m ³ /s)	(m)	(kg/s/m)			(m/s)		Ave	Min	Max
A1	0.003 3	0.006 0	0.071	0.000 0	0.002 2	0.002 5	0.269	0.269	44.5	20	60
A2	0.003 3	0.008 2	0.081	0.000 0	0.001 8	0.002 2	0.261	0.261	48.6	32	64
A3	0.001 2	0.003 6	0.018	0.000 0	0.002 3	0.000 8	0.021	0.021	5.7	0	44
B1	0.001 2	0.004 9	0.062	0.000 0	0.002 0	0.002 0	0.181	0.181	22.8	0	52
B2	0.003 3	0.015 2	0.107	0.000 0	0.003 1	0.003 5	0.554	0.554	60.5	44	64
SF	0.001 2	0.009 3	0.073	0.003 1	0.001 5	0.001 4	0.156	0.156	13.4	0	52
C1	0.001 2	0.011 7	0.072	0.006 1	0.001 2	0.001 2	0.130	0.130	1.4	0	6
C2	0.002 0	0.011 7	0.083	0.006 9	0.004 9	0.004 4	0.543	0.543	27.8	2	52
C3	0.002 0	0.015 7	0.096	0.006 9	0.004 3	0.003 9	0.554	0.554	29.2	20	52
C4	0.002 0	0.022 1	0.118	0.006 9	0.003 6	0.003 3	0.574	0.574	37.4	24	63
D1	0.004 7	0.014 7	0.089	0.006 9	0.001 1	0.001 9	0.250	0.250	0.4	0	3
D2	0.004 7	0.014 7	0.099	0.006 9	0.001 9	0.002 3	0.340	0.340	27.9	7	58

2.3 Results and Discussion

The average depth of free space was calculated as the mean of the average value for each hemisphere. In run A3, where the sand levels were very low, a similar averaging procedure was used, but with reference to the gaps between hemispheres, rather than the hemispheres themselves.

The measured depths are given in Table 1, and are also plotted against Shields parameter for sand in

Figure 2. Results of Jonker (2002) for different sand sizes are also plotted. (In each case, the size indicated is the median sand diameter.) Jonker (2002) also used the final scour pattern from previous runs as the starting point for several successive runs. It is clear from their results that for some experimental runs, no additional scour was observed, and these runs are not included.

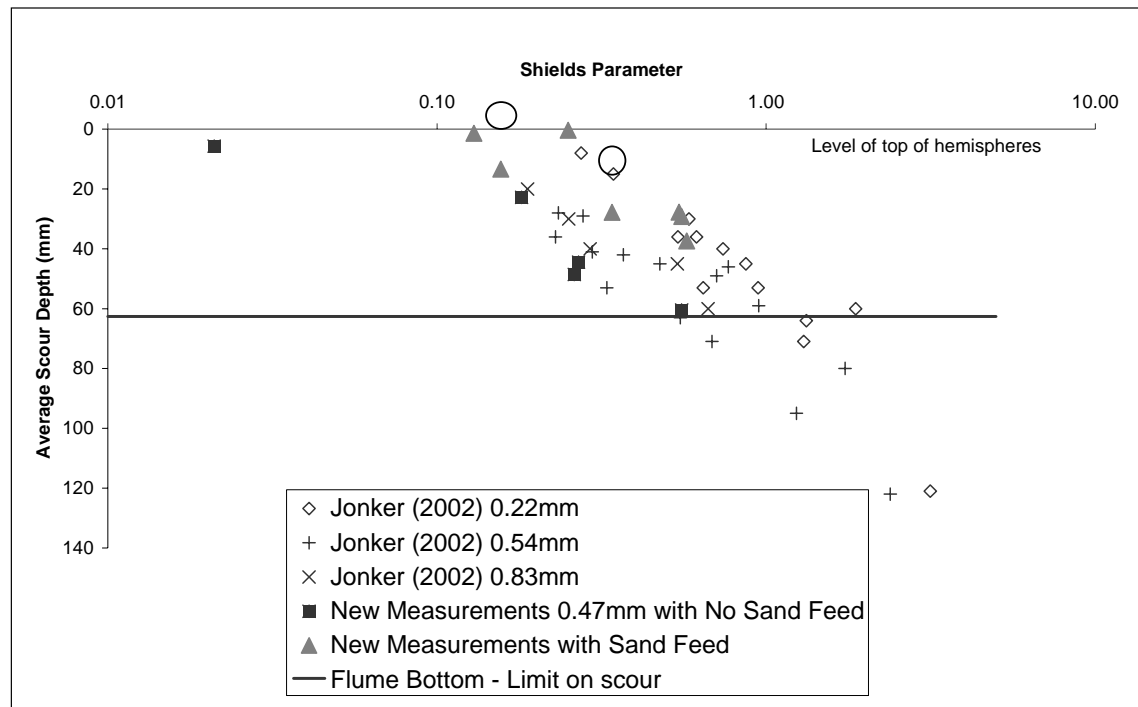


Figure 2: Results of Equilibrium State Experiments

The relationship between Shields Parameter for sand and scour depth is clear, despite considerable scatter. Although there appears to be some difference between the results for the different sand sizes used by Jonker (2002), no directional trend is evident. New data is in agreement with previous results of Jonker (2002), provided that where Jonker (2002) indicates a range of depths of free space, the maximum should be used. The current experiments used lower Shields parameters than those of Jonker et al. (2002), and thus extend the range of available data. The supply of sediment decreases the scour depth. However, the results with sand supply depend to a large extent on the scour patterns produced. In most tests, the formation of longitudinal paths of deeper scour was actively prevented by adjusting the shape of the ramp feeding sand into the test section. In this case, the trend is fairly uniform. However, in tests SF and D2 (circled in figure 2), a deep scour path was still produced, and in these cases, the average scour depth was increased.

The equilibrium state can be defined in any desired way. However, at this stage, it would be impractical to attempt to describe the state in terms of the small-scale scour patterns produced. Neglecting the effect of these patterns nevertheless introduces considerable inaccuracy in the prediction of average parameters, such as exposed area or average depth of free space. Further inaccuracies are introduced in a sand budgeting model through the necessary conversion of sand quantities to the desired state description, because such conversions cannot be predicted precisely, as evidenced by the data of Osmundson et al. (2002). Nonetheless, it is hoped that prediction accuracies comparable with those of sediment transport methods may be produced.

3 Experiments to Determine the Progression of Scour

3.1 Aims

- To quantify the rate at which sand scour progresses downstream.
- To quantify the time required for scour at an initial position.

3.2 Setup

The same flume, sediment feeder and instrumentation were used as for the previous experiments. However, coarser graded silica sand with a size range of 0.5 to 1.18mm (0.7mm nominal size) was used. To represent cobbles, smaller 73mm diameter concrete hemispheres were used, and these alternate in rows of four or five hemispheres across the full flume width. Three measurement sections, numbered 1, 2 and 3 were included with their centres 1.91m, 3.14m and 4.73m respectively from the upstream end of the test section. On nine hemispheres in each measurement section, rings were painted at specified radii, centred at the top of the hemispheres, rather than at specified depths. Since the progress of scour was to be observed, each test was started with the gaps filled with sand approximately to the top of the hemispheres.

3.3 Procedure, Calculations and Sample Results

During each test, at frequent intervals, the scour depth on individual hemispheres was read. These readings include a minimum, maximum and estimated average radius to the top of the sand. The estimated average radius to sand is converted to a depth of free space, and a proportion of surface area covered. Two tests performed are listed in Table 2. The effective flow depth is calculated as discussed previously. Resistance, and thus slope and depth changed as scour progressed, as is shown in the table.

Table 2: Test conditions for first two Progression Rate Experiments

Test	Time	Bed Slope	Dis-charge	Effective Flow Depth	Water Surface Slope	Energy Slope	Shear Velocity
			(m ³ /s)	(m)			(m/s)
E1	Near Start	0.004 2	0.023 7	0.158	0.000 4	0.000 4	0.025
	Near End			0.169	0.001 1	0.002 2	0.042
E2	Near Start	0.004 2	0.023 7	0.161	0.001 2	0.001 0	0.041
	Near End			0.177	0.001 9	0.001 7	0.055

The results of one test run will be presented as an example of the information produced. Test E2 has been selected as an example.

In order to estimate the progression of scour, the readings for average scour around a particular hemisphere are interpolated linearly with respect to time. The average depth of free space or plan area of hemispheres exposed at any one of the three measurement sections at any time is then estimated as the average of these interpolated readings at that time for the nine hemispheres within that measurement section. An example of these results is given in Figure 4.

The way in which the rate of progression of scour is calculated from these initial results will be explained by means of an example, which is illustrated on the appropriate figures with arrows. From figure 3, it can be seen that it took 1 hour and 15

minutes for measurement section 1 to reach 60% exposure. It took 2 hours and 44 minutes for measurement section 3 to reach 60% exposure.

The state of 60% exposure can therefore be seen to have progressed the 3.5m between measurement sections 1 and 3 in a period of 1 hour and 29 minutes. The rate of downstream progression of this scour is thus 3.5m divided by 1 hour 29 minutes, which is equal to 2.0m/h. This rate is plotted in

Figure 5 against the corresponding exposure of 60%. Similarly, the scour rates between other measurement sections, and for other exposures (40%, 50% and 70%) are also plotted in figure 4 for this test.

As mentioned previously, it took 1 hour 18 minutes for measurement section 1 to reach 60% exposure. However, measurement section 1 is located 1.91m from the upstream end of the test section. At the calculated scour rate of 2.0m/h, it would have taken 58 minutes for this scour to progress from the start of the test section to measurement section 1. The extra 20 minutes actually taken may be considered as an additional period required for initial scour to this level at one longitudinal position. This additional initial scour period is plotted in figure 5, again against the corresponding 60% exposure. Similarly, the initial scour periods for other exposures were also calculated, and are also plotted.

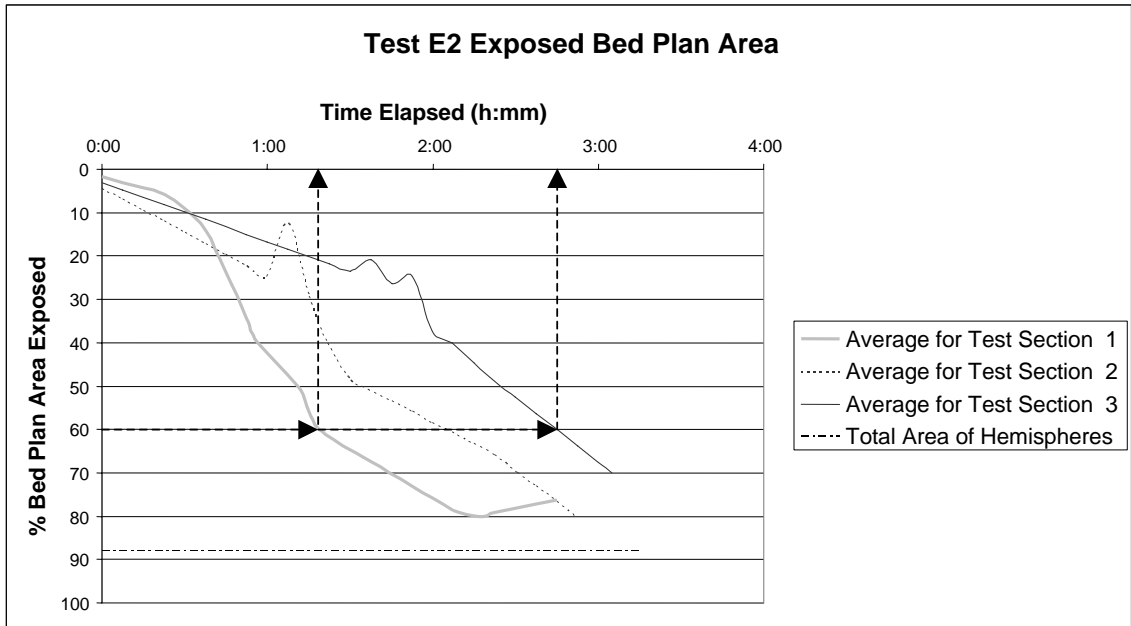


Figure 4: Example of Scour Depths per Test Section

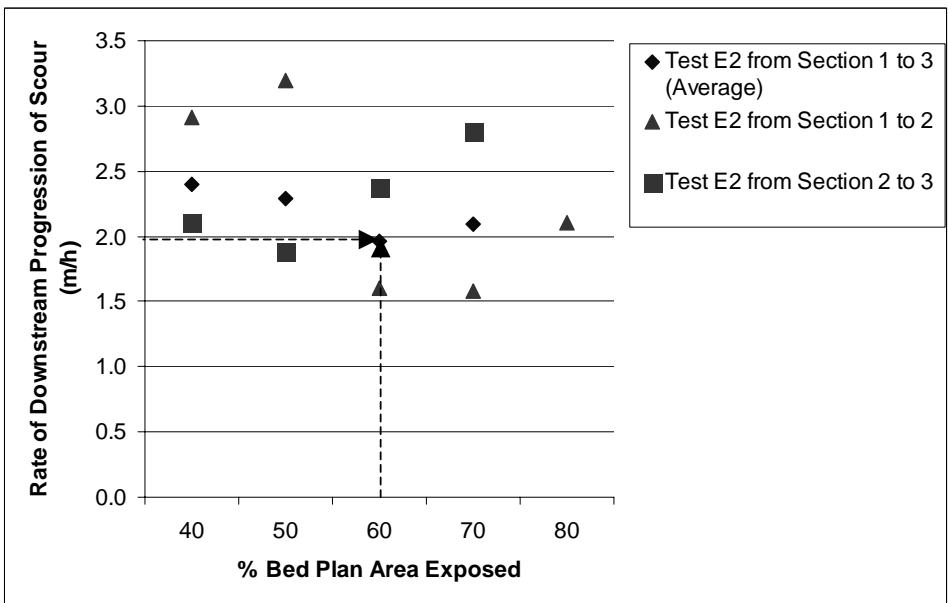


Figure 5: Example of Rate of Downstream Progression of Sand Scour

3.4 Discussion

The initial results presented here indicate that, while there is considerable variation in progression rates, even within a single experimental run, a rough estimate can be made. The calculated additional period required for initial scour appears so far to follow a more defined trend. Further experiments will enable both scour rate and initial scour period to be linked to hydraulic parameters, and sand feed rates.

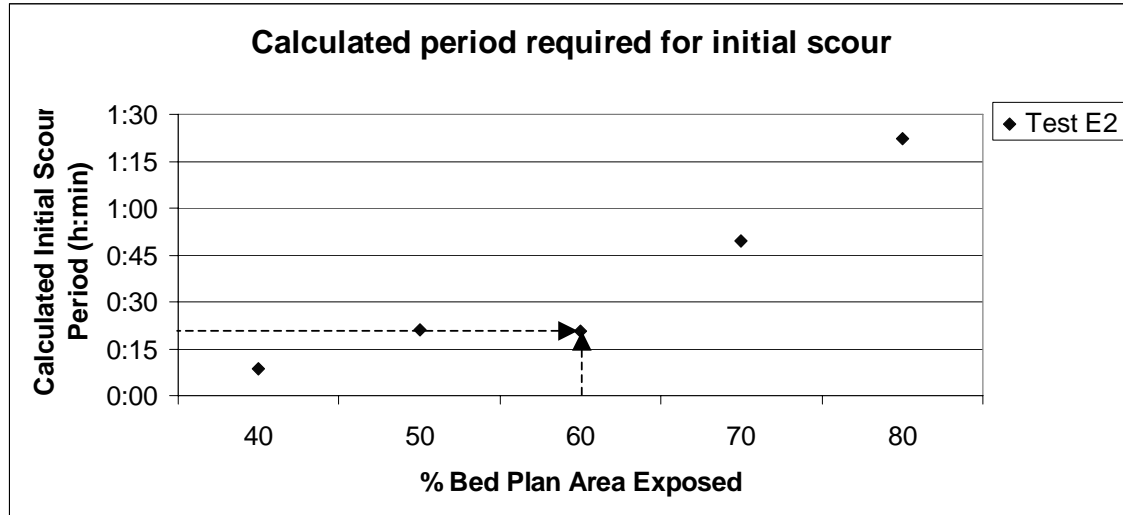


Figure 7: Example of Calculated Period Required for Initial Scour at a Point

4 Small-scale Sand Budgeting

4.1 Model Description and Main Relations Used

Based on the experiments described above, a model is being developed which aims to predict changes in embeddedness of the surface layer of a cobble bed. It follows the equilibrium state approach described in section 1.4. The model is being programmed with a combination of Microsoft Excel and Visual Basic. The model area is divided longitudinally into cells. A single size is used to represent the cobble or boulder size in each cell. A single particle size is used to represent the sand fraction for the entire model area.

The main relations required are:

- A relation to predict the equilibrium embeddedness state for a cell, specifically for the case where there is no sand supply

The effect of sand supply is accounted for by:

- A procedure which routes incoming sand between cells and
- A geometric relation between sand quantities and the state which they produce

Rates of change are included through:

- An equation to represent rate of scour within a cell
- The rate at which scour progresses along the length of the modelled area is controlled by the cell length and the length of the time step used in calculations.

Limiting conditions are also included:

- Since surface flushing is considered, the depth of free space limited to a maximum of 1.1 times the representative cobble or boulder size in a particular cell. Alternatively, exposed surface area will be limited to 100%.
- Critical condition for cobbles: The critical shear velocity for motion of the cobbles / boulders within each cell is calculated as: $\sqrt{9.81 \times \text{cobble size} / 13}$. Whenever this critical condition is reached, the state of embeddedness is reset to a low, but arbitrary value.

4.2 Input Data Required

- Characteristics of the modelled area: Length, width and representative cobble size in each cell
- Flow Data – either as a time series of flowrate and sand inflow, or as a fixed flowrate and sand inflow for a specified duration
- Representative sand diameter
- Initial condition: initial embeddedness condition in each cell
- Hydraulic information: Selected calibrated flowrates, where the shear velocity in each cell is specified for each calibrated flowrate. It is intended that these shear velocities will be derived from some hydraulic model run at the

calibrated flowrates. They may be used directly, or to calculate other hydraulic parameters, such as Shields Parameter.

5 Conclusion: Applicability of the Equilibrium State Approach

Embeddedness of cobbles on river beds is a habitat characteristic of high biological importance. Compliance with the National Water Resources Strategy (DWAF, 2002) therefore requires the development of methods for the quantitative and descriptive prediction of embeddedness. The equilibrium state approach has the potential to provide such predictions.

The experiments performed to predict the equilibrium state demonstrate that such states for embeddedness of cobbles do indeed exist, and can be predicted approximately based on Shields Parameter for sand. Figure 7 suggests that the rate at which this state is approached can also be specified. The equilibrium state approach is therefore applicable to prediction of embeddedness. Approximate relations have been developed to predict the equilibrium state and the time rate at which this state is approached, both at a particular longitudinal position and along a modelled length of river.

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